Configuring a machining operation as a Constraint Satisfaction Problem

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Abstract. The problem of configuring a machining operation is complex (many parameters and many interactions between parameters) and is generally achieved thanks to expert heuristic knowledge. Indeed, the configuration of a machining operation is often carried out according to a specific procedure: choice of a kind of operation and of a kind of machine, then choice of a set of tools and at the end selection of cutting conditions.
We propose in this paper a general framework for the configuration of a machining operation based on a constraint representation and manipulation. We first present a model of the decision variables (such as the machine, the tool, the insert or the feed rate), the non-decision variable and the constraints between variables. An overview of the 32 identified constraints is given in the paper. Even though it is not exhaustive, the basic constraints of the domain are represented. A typology of the constraints to be manipulated is then given leading order to a specification of algorithms for search and consistency checking that may allow to manage these kinds of constraints.

1. Introduction

In recent research work, one may notice an increasing interest in the development of tools for the configuration of machining operations. The problem of configuration of a machining operation may be described as follows: in order to ensure the machining of a part, several parameters for the machining operation have to be defined. These parameters are for instance the kind of operation that will be performed (e.g. milling, drilling…), the machine on which the operation is to be performed, the tools that will be used, the feed rate and so on. The choice of the parameters should be achieved according to technical constraints (some tools do not adapt on some machines, the energy necessary for the operation should be available on the machine…). Moreover, optimisation criteria are often defined in order to select a solution among the set of configurations that respect the technical constraints.

This problem is very complex essentially because of the combinatorial characteristics of the domain of search. The complexity of the problem leads people who carry out machining process configuration to follow a linear selection of the parameters and therefore to build progressively a solution without taking into account the whole set of technical constraints. Several decision support tools are provided, especially by tool manufacturers. These tools enable to select easily some of the parameters according to a specification of the context. For example given the characteristics of a tool and wear and of the workpiece, such a system may compute a relevant value for the feed rate and the depth of cut in a turning operation. However, once again, these tools are used in a specific step of the configuration process, when the major part of parameters is already defined. We observe that the problem of machining process configuration remains most of the time based on empirical data layout and methodologies. This leads us to propose an explicit representation of the decision variables and of the technical constraints in order to provide the user with an interactive decision support system that allow him to develop his own strategies for the problem solving.

A more general field of study may be related to the problem of machining process configuration: the domain of manufacturing product configuration. Indeed, in the past few years the need of interactive decision support system in the field of product configuration has been clearly emphasised [1] The objective is generally to configure a product consisting in an assembly of components chosen in a set of possible ones. Therefore the considered domains of choice are generally discrete which is not the case for machining process configuration where continuous domains are used.

A recent work [2] has emphasised the need of interactive configuration tools taking into account both discrete and continuous constraints for example in the field of Computer Aided Design. This works points out and explains the relevance of a constraint based approach for configuration compared to the rule based approach. Two kinds of constraints are depicted:

- activity constraints [3] which enable an incremental introduction of the variables and of the constraints,
- compatibility constraints which are the constraints of the domain.

The formalism used to represent the objects is close to Logic Programming which enable an easy implementation with a Constraint Logic Programming language. This is, to our opinion a difficult task for designers to express and structure their knowledge within this kind of formalism. Moreover, the intrinsic object nature of the knowledge is not used in the algorithmic manipulation of the constraints.

That is why we propose an integrated framework called KASKOO for an interactive decision support system generator based on an object oriented knowledge representation and acquisition module and a methodology of knowledge acquisition. The acquired knowledge will then be used thanks to various and generic manipulation techniques, such as constraints problem solving (as described in this paper) or case based reasoning.

2. Domain and constraint overview

According to the references [4] and [5], the following domains and constraints act upon the configuration of a machining operation. The domains identified (continuous domains are in italic and discrete domains are in normal face) in our study are:

X1 : profile of a workpiece

X2 : kind of machining operation

X3 : kind of machine (lathe …)

X4 : tool holding device

X5 : tool shank

X6 : clamping system

X7 : type of insert
X8 : precision
X9 : cut force (Fv)
X10 : feed (f)
X11 : depth of cut (ap)
X12 : energy required
X13 : specific cutting energy
X14 : cutting speed (Vc)
X15 : coefficient of Taylor relation (Cv)
X16 : tool life (T)
X17 : coefficient of empirical Taylor relation (K)
X18 : available energy
X19 : tool material
X20 : workpiece material
X21 : corner radius (Rε)
X22 : surface roughness of workpiece
X23 : stability
X24 : major cutting edge angle (Ϗr)
X26 : effective length of cut (L)
X28 : max value for cutting speed
X29 : max value for feed
X30 : cutting energy (Nc)
X31 : feed force (Ff)
X32 : feed energy (Nf)
X33 : maximum precision

The constraints on the domains are the following:

C1 (X5,X7) : Adaptation constraint between the kind of tool shank and the type of insert. Cutting tool manufacturers generally provide with a list of valid couples (tool shank, wear).

C2(X6,X7) and **C3**(X5,X6) : There exist four normalised clamping systems. The choice of a clamping system is linked to the choice of the insert (C2) and of the tool shank (C3).

C4(X4,X5) : Adaptation constraint between a tool shank and a tool holding device.

C5(X3,X4) : This constraint links the kind machine and the tool holding devices that may be adapted to it. A turning machine may for instance accept several tool holding devices.

C6(X2,X3) : A machine can achieve several kinds of machining operations and a given machining operation can only be processed on specific machines. This constraints links types of machining operations and types of machines.

C7(X1,X2) : The workpiece profile may determine the relevant machining operation required.

C8(X6,X9) : The cut force must be tolerable for the cutting tool. Over a given value of cutting force the tool begins to plow and the result of the machining operation may not be satisfying. This constraint therefore links the cutting tool and the cutting force Fv, giving an upper limit for this latter.

C9(X1,X5) : In order to machine a profile, only some tool shank are acceptable. Indeed, it is necessary that the shape of the tool is acceptable for the profile to machine. Manufacturers provide with a list of couples (tool shank, profile).

C10(X7,X8): The machining tolerances are limited by the precision of the insert. Indeed, cutting tools ensure a maximum tolerance and it is impossible to machine a workpiece with a smaller tolerance.

C11(X7,X10,X11,X14,X16,X20) : The chip breaker diagram: for a good machining , it is important that the chip is fragmented. The fragmentation of the chip for a given cutting speed Vc and feed rate f. We obtain experimentally a working zone where the couple (Vc,f) leads to a broken chip.

C12(X19,X20) : The characteristics of the workpiece material influence the choice of a tool material. The coupling (tool material/workpiece material) influence the feasibility of the machining operation. Therefore, it is necessary to chose the tool material according to the workpiece material.

C13(X2,X19) : The tool materials have various behaviour according to the type of machining operation. For instance, a high speed steel has a good behaviour in the finishing cut and a carbide is better adapted to a rough machining.

C14(X16,X20) : The tool life depends on the tool material .

C15(X18,X19) : The tool material limits the acceptable cutting force for machining

C16(X16,X21) : The tool life is limited by the corner radius Rε of the insert. The smaller the corner radius is, the quicker the wear occurs.

C17(X10,X21,X22) : The surface roughness of the workpiece is function of the machining conditions, of the corner radius Rε and of the feed rate f of the tool. For instance, for a turning operation, surface roughness Ra may be determined as follows :

$$Ra = \frac{f^2}{18\sqrt{3}R\varepsilon}$$

The value of surface roughness is generally a maximum value. The roughness obtained after machining should respect the limit given in the specifications.

C18(X21,X23) : The stability is linked to the corner radius Rε. With a to small corner radius, vibrations may appear.

C19(X14,X15,X16,X17) : The tool life is linked to the cutting conditions. The simplified Taylor relation gives elements which influence the life duration T. The cutting speed Vc is related to the coefficients Cv and K. These coefficients sum up other machining parameters. Cv is generally obtained thanks to an experimental evaluation of the wear law. K is obtained thanks to constraint C20.

The empirical Taylor relation is :

$$T = Cv.Vc^{K}$$

C20(X2,X17,X19,X20) : Determination of the coefficient K: K is a summary of static parameters of the machining operation. It is function of the tool material, of the kind of machining operation and of the workpiece material to machine. The value is generally given by a table.

C21(X12,X18) : The available energy at the spindle level is the maximum limit of the energy required for the machining operation.

C23(X11,X24,X26) : The effective length of cut L is function of the working major cut edge angle Κr and of the depth of cut. This effective length cutting of cut must not overcome a maximum value which is function of the nominal length of cut l and of the kind of insert.

C24(X10,X21) : The value of the feed rate is limited by the corner radius Rε. A bigger corner radius enables a greater feed rate.

C25(X2,X9,X10,X18,X20,X24) : The specific cutting energy Ks depends on the main cut effort Fv and of the surface of the cut section.

$$K_s = C \times k_1 \times k_2$$

Where C depends on the workpiece material, k1 and k2 are function of the working major cut edge angle. For turning we for instance have:

$$K_s = C.(f \sin \chi_r)^n$$

C26(X9,X10,X11,X13) : The cut force Fv depends linearly on the specific cutting energy Ks, on the feed f and of the depth of cut a_p according to the following relation:

$$F_v = K_s.f.a_p$$

C27(X14,X28), **C28**(X10,X29) and **C29**(X8,X33) : The cutting speed Vc is limited by the characteristics of the machine. Indeed, there is a minimum and a maximum value for Vc. Similarly, there is a range of acceptable values for the feed rate f and the maximum precision.

C30(X9,X14,X30) : The cut energy Nc is the result of a coupling between the cut effort Fv and the cutting speed.

C31(X9,X24,X31) : The feed force Ff is function of the cut force Fv and the direction of the major cutting edge angle κr.

$$Ff = Fv.(0{,}15 - 0{,}1.\cos \chi_r)$$

C32(X10,X31,X32) and **C33**(X12,X30,X32) : The feed force Ff and the feed rate f lead to the necessary energy for feed Nf. The sum of all these energies gives the consumed energy which must be less than the maximum energy of the machine.

3. Constraint typology and proposed solutions

According to the listed domains and constraints, a typology of the constraints to be manipulated can be determined and therefore, an algorithm for search and consistency checking that allows to manage these kinds of constraints can be specified. The following characteristics should be taken into account in the management of constraints:

- Constraints may be of arity
  - 2 (binary constraints),
  - > 2 (n-ary constraints).
- Constraints may be on:
  - Discrete domains,
  - Continuous domains,
  - Both discrete and continuous domains.
- Constraints may be described
  - in extension (table),
  - in intention (predicate).

Moreover, in order to ensure the interactivity of the Decision Support System, the management of the constraints should be dynamic (add / remove domain, value, constraint).

The DnGAC-4 algorithm [6] has therefore been selected. This algorithm deals with dynamic constraints of arity n on discrete domains.

The problem of constraints on continuous domains and on both discrete / continuous domains is not directly taken into account by the algorithm. Therefore, we are currently aiming at finding a relevant approach for these cases.

The first approach is to discretize domains into discrete values. The obtained discrete set may then be treated using DnGAC-4 algorithms.

The second approach an interval propagation technique such as 2-B-consitency or 2-B(w)-consistency algorithm [7] in the case of intervals.

A third approach is to use techniques described in [8] based on a decomposition of the constraints into quadtrees (for binary constraints) or octrees (for ternary constraints) and the manipulation of such representation. The criteria for selecting one approach in our problem solving remain not very clear for now.

4. Conclusion:

In this paper we present the problem of configuration of a manufacturing operation. This problem, even though important in practice, is scarcely addressed in research papers. The CSP techniques offer a relevant framework for the modelling of the problem. Therefore, we propose a description of the domains and of the constraints in the case of a machining operation. This enumeration leads to a typology of the constraints that should be manipulated by the solver. In the case of n-ary constraints on discrete domains relevant algorithms, such as DnGAC-4, may be easily found. However for constraints on both discrete and continuous and on continuous domains several alternatives remain to explore.

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